CONTRAST SENSITIVITY — A MORE REALISTIC MEASURE OF VISUAL FUNCTION

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Abstract
Terms used in the study of spatial contrast sensitivity are defined and the basic neurophysiology related to the Cam Vision Stimulator is briefly mentioned. An outline of the development of the concept of modulation transfer function and an explanation of its practical value in comparison with visual acuity tests includes discussion on the use of Arden Gratings.

The advent of the Cam Vision Stimulator and the Arden Gratings has brought a new terminology to the practising orthoptist. It is important that she knows exactly what is meant by "spatial contrast", "spatial frequency", "contrast sensitivity" and the like and how such terms are used to describe visual function. This paper will attempt to explain the basis of the new tests, and the reasons why they are so superior to the Snellen visual acuity and similar tests (E, Landolt C. Sheridan-Gardner etc.)[1]

Definitions.

A *Grating* is a regular pattern of light and dark bars, usually presented clinically as vertical bands.

A *Square Wave* grating denotes a pattern of light and dark bands where the change from light areas to dark, and from dark to light, is instantaneous. (Figure 1, D)

A *Sine Wave* grating is a pattern of light and dark bands in which the change in brightness follows the path of a sine wave. This results in a continuous change so that the brightness is constantly altering throughout the whole cycle from light to dark and dark to light. (Figure 1, A,B,C)

Spatial frequency is defined as the number of complete cycles of change from dark to light and back, in a grating pattern, per degree of visual angle: (therefore, for any given grating, the spatial frequency varies with varying viewing distances).

Spatial Contrast expresses the difference between the light and dark parts of the pattern. If the pattern varied between pure black and white the contrast is said to be 1.0. If the bands varied from dark grey to light grey the spatial contrast might be, say 0.3. At some frequencies humans can detect spatial contrast of less than 0.01. (Some authors use "percentage contrast" where the above figures are multiplied by 100).[2]

Contrast sensitivity expresses the ability of the visual system to detect spatial contrast. As the contrast of a test screen is gradually raised from zero, (i.e. uniform illumination), the level of contrast at which the light and dark pattern of the frequency being tested is first detected is termed the threshold contrast for that frequency. Contrast sensitivity is expressed as the reciprocal of the spatial contrast at which the pattern is first detected. Thus if the threshold contrast was 0.01, the contrast sensitivity would be 100.

The Contrast Sensitivity Function is a *curve* showing the contrast sensitivity at each spatial frequency over a range, usually from 0.1 to 40 cycles per degree in humans. (30 cycles is approximately equivalent to 6/6 in Snellen's type tests. Human vision is most sensitive to spatial frequen-

cies of around 3 cycles per degree, not 30 cycles per degree.) (See Figure 2)

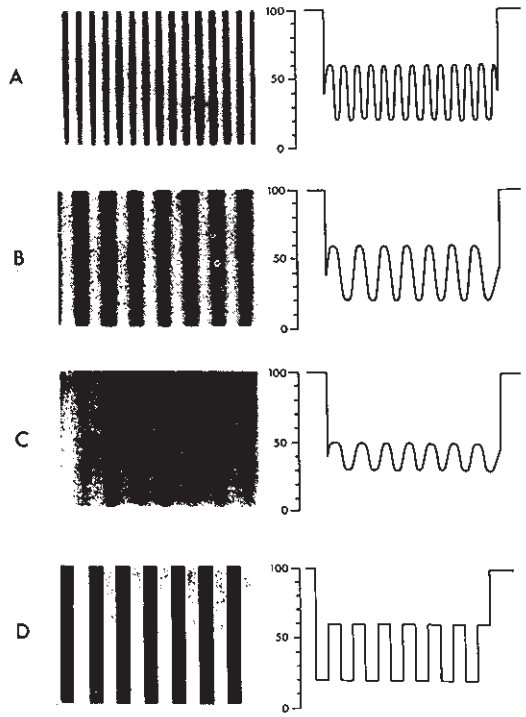

FIGURE 1
A,B & C are sine wave gratings; D is a square wave grating. The spatial frequencies of gratings B, C & D are equal but that of A is higher. The contrast of gratings A, B & D is equal but that of C is lower. All four gratings have the same average brightness overall. Humans are most sensitive to spatial frequencies of about 3 cycles per degree which corresponds to grating A, viewed at 85 cm (From G. B. Arden, B.J.O.[6])

In a particular individual the curve might show overall depression; or loss of sensitivity over a limited range of frequencies e.g. high frequency loss, or low frequency loss, just like an audiogram.

Just as we can define the ear's sensitivity to various sound frequencies (cycles per second or Hertz) with an audiogram, we can define the eye's performance with a "visuogram" or a "contrast sensitivity function". This will record the eye's sensitivity to various spatial frequencies (cycles per degree of visual angle) as a reciprocal of a threhold contrast, for each frequency. The words "contrast sensitivity function" simply mean that the visual system is tested at each of a significant number of spatial frequencies for its ability to detect contrast.

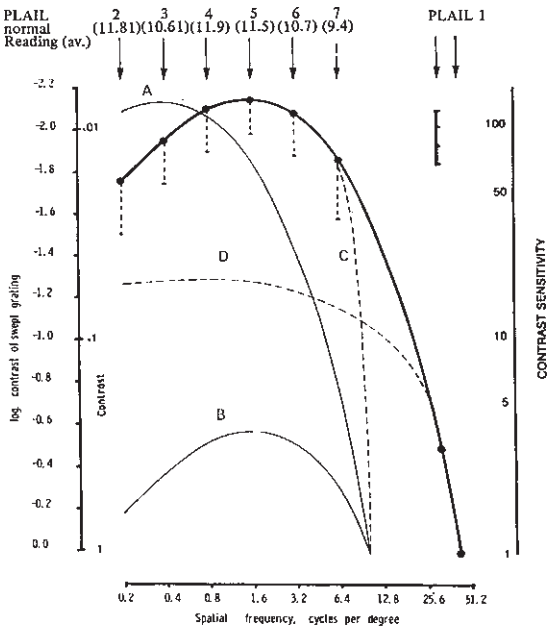

FIGURE 2
The heavy line is the normal human contrast sensitivity curve. The arrows above show (2-7) the points on the curve tested by the 6 Arden gratings. Curves A & B show two different types of amblyopia in whom visual acuity is equally depressed, but obviously B has a much more serious loss of visual function. Curve C shows high frequency loss which often occurs with refractive errors. D shows the curve of a patient with normal visual acuity but severe qualitative loss of vision due to depressed low spatial frequency sensitivity. (Modified from G. B. Arden, B.J.O.[6])

The amazing thing is that this is apparently just what the visual system actually does. It analyses the visible world in terms of the relative size (spatial frequency) of adjoining areas of differing brightness (contrast) and the orientation of the lines of contact between those areas (from 0° to 180° – not just vertical bars). The visual cortex is arranged in fine layers (or lamina) like a layered cake. In each lamina the cells are all responsive to a specific spatial frequency. At the same time the cortex is arranged in columns, from the surface to the deeper layers; all the cells of each column have the same orientation sensitivity.

So a needle penetrating vertically (to the surface of the brain) will meet cells which, at all depths, are all sensitive to the same orientation of spatial stimuli; but as it goes deeper the cells have spatial frequency requirements changing from lamina to lamina. A needle parallel to the surface

would meet cells of the same spatial frequency requirement but differing in orientation sensitivity from column to column.[3] This is the way the brain structure is organised to analyse form and contrast. On this basis Fergus Campbell[4] designed the Cam Stimulator to activate cells of all types whatever their spatial frequency or orientation sensitivities might be.

EVOLUTION OF CONCEPT

The main impetus for the "new" techniques began in World War II.

Just as the practice of orthoptics itself received a great boost when the binocular vision of Allied airmen became a matter of vital importance, so the concept of spatial frequency analysis evolved from the wartime necessity to obtain better definition in aerial photographs of enemy targets.

Aerial camera lenses used to be assessed by their "resolving power" that is their maximum ability to show high contrast fine black lines on a white background as discrete and separate images. (This test is analogous to Snellen's visual acuity tests — and just as ineffectual). Costly new lenses were manufactured with very high resolving power, but their pictures often seemed harder to interpret than those of the old lenses. Experts argued heatedly about the relative advantages of their favourite lenses in esoteric terms similar to those used by modern art critics. There was no way of describing lens performance or the difference between various lenses in absolute terms.

But gradually it was realised that most of the detail in aerial photographs was of *low* contrast, often due to haze or fog, and overall interpretation often depended on recognition of the pattern of relatively large areas i.e. low spatial frequency.

So it became obvious that tests of high contrast fine lines (i.e. high spatial frequency) were not as important as tests of low contrast, over wide areas (i.e. low spatial frequency). This suggested the method of Fourier analysis where *all* possible spatial frequencies are recorded in terms of their relative contrast.

Fourier was a French mathematician who discovered that, no matter how complicated a pattern of energy input may be, it can be expressed accurately as the sum of a variety of sine waves at different frequencies and amplitude (contrasts). This is easy to understand with *sound* energy where the noise of a whole orchestra can be divided up into the component sound *frequencies* and *amplitudes* (loudness) of each instrument. The amplitude expresses the intensity of the sound energy (contrast from peak to zero of the sound wave).

Similarly, every picture can be accurately described in terms of the *spatial frequency* and relative light *intensity (contrast* of black and white) of its component features. Now we have a mathematical expression (a "function") to describe the picture. Any change in the picture changes ("modulates") the function. So if the picture is copied ("transferred") by a lens we can express the new copy as a *"modulation transfer function"*.

This accurate and comprehensive method of describing lens performance was universally adopted by lens makers in the 1940's, and later used to describe the "modulating" effect of various films, printing processes and accessory optical systems. It is the basis of the production and computer improvement of pictures taken in space by satellites and relayed to earth by radio transmission. These picture transmissions are often subject to considerable interference but the computer can calculate the degree of "modulation" in the radio "transfer" and correct the picture accordingly.

Some research workers used the term "modulation transfer function" (MTF) to describe visual system performance but most workers now use the term "spatial contrast sensitivity". Until recently clinical ophthalmology adhered to the old method of Snellen's high contrast, high frequency resolution tests — fine black letters on a white background, ignoring the now obvious need to describe low contrast and low frequency vision. Visual research laboratories changed to the new contrast sensitivity methods over fifteen years ago.[5]

PRACTICAL APPLICATION

All clinicians should now be aware that Snellen's and related tests describe not only a very small area of visual field (6/6 cover less than 1/10 of 1°) but also a very limited part of the less sensitive, extreme high frequency region of visual function, ignoring the wider areas of much more sensitive low frequency function.

There are a number of survival situations where foveal (Snellen's) vision is irrelevant but low contrast low frequency spatial sensitivity is supremely important: for example, flying an aircraft through hilly country in low cloud; rescue work in smoke or fog; or location of land marks or individuals in murky underwater environments. The authorities are very strict about visual standards (Snellen's) of pilots, firemen and police rescue staff. It is now obvious that they are testing the (often) irrelevant end of the spatial frequency function.

One reason for the delay in progress is that, until recently, suitable test patterns could only be produced on C.R.O.'s (cathode ray oscilloscopes – the original T.V. screens). With these instruments accurate mean lighting and contrast levels could be maintained for any spatial frequency grating and any contrast level, but the test procedures take too long for standard clinical application. The total amount of light coming from the test screen *must* be kept constant, whatever the contrast and whatever the frequency. The Arden book of gratings frees the clinician from the C.R.O. adjustments but accurate control of lighting and viewing distance are still of the utmost importance. Arden suggests a 60 Watt globe 40 cm above the table on which the book is placed, in addition to normal room lighting. Viewing distance is 57 cm.[6]

In the book of Arden gratings (1st edition) each of the 5 pages has a single spatial frequency (except one which has 2 patterns) but the contrast varies from top to bottom of the page. The operator covers the test plate except for the lowest contrast area and gradually moves the cover to expose more and more of the higher contrast areas. (The cover should be a non contrasting neutral grey.)

The Arden grating plates are printed by a computer. If you could count the minute dots that make up the grey pattern on the page you would find exactly the same number of dots across the page on every horizontal line, from top to bottom of each page. In the zero contrast region (at the bottom of the page), the tiny black dots are all equally spaced across the page. In the higher contrast regions the dots are crowded and then spread out, repeatedly across the page, to form the darker and lighter parts of the spatial frequency pattern. Equal (or controlled) brightness and contrast levels are assured because the computer prints an equal (or controlled) number of dots for all patterns.

The operator has to decide, from the patient's response, at what level of contrast the spatial frequency is first detected. This level is read off an arbitrary scale (1-20), printed on the side of the plate, and is recorded for each plate (or frequency), thus forming a contrast sensitivity function for that patient. A total score of > 78 for all six plates is said to be abnormal, as is a difference > 5 between the right and left eye score.

CLINICAL FINDINGS

The fine close packed pattern of high spatial frequency is only detectable by the high acuity central foveal cells while the lower spatial frequencies are detected by much wider areas of the retina. Thus the Arden Gratings of low frequency give us a much better way of defining amblyopia – expressing its effect over a wide area. This technique has shown that there are two basic groups of amblyopes. Those with overall loss of sensitivity at all spatial frequencies and those with depression of sensitivity only at the high frequency region of the function. They may both have equal visual acuity, but obviously their visual abilities are quite different.[7]

In glaucoma Snellen acuity may remain unchanged in the presence of severe optic nerve damage and field loss. In contrast, Arden grating tests may show abnormal results very early in the disease before disc and field changes are demonstrable, and the scores become greater with increasing severity of the disease. The test can be scored so that a very sharp distinction may be made between normal and glaucomatous eyes.[8]

The *low* frequency gratings have another interesting and useful property – they are relatively unaffected by refractive errors, movement or changes in fixation (as in babies or people with nystagmus).

Contrast sensitivity tests can be used to test visual function when a cataract patient's vision is so low, due to opaque lenses, that he can hardly read any figures on a test chart. Spatial frequency gratings are generated on the retina itself as interference patterns, formed by the interaction of two laser beams projected into the eye by a special slit lamp. Thus the surgeon who cannot visualise the retina obtains a more accurate visual prognosis than is available by any other method.[5]

Contrast sensitivity tests give us a sensitive measure of visual loss in diffuse nerve diseases such as multiple sclerosis, where such loss is sometimes the only positive sign of early or dormant disease.[9]. A number of patients whose acuity is 6/6 in each eye describe a *qualitative* loss of visual acuity which we cannot measure at present except with contrast sensitivity tests. Legally they have normal vision. Functionally this is not true. (See Fig. 2). Such patients may be quite dangerous driving or flying in foggy conditions where low contrast, low spatial frequency sensitivity is very necessary.

Visual assessment of infants, animals and brain damaged patients requires objective rather than subjective methods. Where visual *acuity* measurements are impossible, contrast sensitivity tests are possible by behavioural reaction to spatial frequency stimuli (even in 5 week old babies[10]), or by interfacing the projected spatial contrast image

with the patient's V.E.R. (Visually Evoked Response).

Thus contrast sensitivity tests provide a much more comprehensive and valuable assessment of a patient's visual function, than visual acuity tests.

The concept is applicable to all visual systems from single cells to the most complex imaginable and it is universally comparable. For example it is now easy to describe how a cat's vision differs from a human's[11]. It is also possible to accurately compare human visual ability with that of any other creature, even a fish or an insect.

CONCLUSION

In conclusion it is appropriate to quote from the British Journal of Ophthalmology; firstly, a 1978 review of a booklet[12] called "Spatial Contrast" (a report on a workshop held in Amsterdam in 1976):

"During the last 2 decades a number of visual scientists have used sinusoidal patterns of specific spatial frequency and contrast to investigate visual function. The approach is powerful, for it permits Fourier analysis to be used in interpretation and modelmaking and provides a common conceptual framework for neurophysiologists, psychologists and ophthalmologists. It has produced an impressive body of knowledge and has considerable further promise both for scientific and clinical investigation."

Secondly, from the Editorial of the British Journal of Ophthalmology (1978) Vol 62, p. 197:

"On present evidence it appears that spatial contrast sensitivity tests will be useful as a visual screening test, in the investigation of visual disturbance when other subjective tests are normal, and in the differential diagnosis in cases of visual loss . . . . . It will be evident that we now have a simple and potentially valuable investigative tool with wide application".

Lastly, from the summary of a paper[1] by Harold W. Skalka (1980): "Patients with various macular and optic nerve abnormalities underwent Snellen acuity, transient VER acuity, and Arden grating testing. Snellen acuity was the coarsest of the 3 evaluations, generally falling after Arden scores and VER acuity had already undergone significant degradation. The Arden gratings appeared to be the most sensitive of the 3 tests, equalling the VER performance in optic nerve diseases and surpassing it in macular diseases."

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